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Aerodynamic Design of Heavy Vehicles Reporting Period October 15, 2002 through January 15, 2003

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Quarterly Report

Reporting Period: **October 15, 2002 through Jan 15, 2003**
Project Title: **Aerodynamic Design of Heavy Vehicles**
Investigators:

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Jim Ross, Dale Satran, Steve Walker, and J.T. Heineck, ***NASA Ames Research Center***
David Pointer and Tanju Sofu, ***Argonne National Laboratory***

1.0 Activities and Accomplishments

1.1 International Conference

Three of the DOE Team members, Fred Browand (USC), Rose McCallen (LLNL), and Jim Ross (NASA), chaired an international conference titled *The Aerodynamics of Heavy Vehicles: Trucks, Busses, and Trains*. It was held at the Asilomar Conference Center in Monterey, California on December 2-5, 2003. Attendees included top scientists and engineers in the field of aerodynamics from universities, government laboratories, and industry. The conference was sponsored by the United Engineering Foundation (UEF) with DOE as a major contributor. LLNL also provided support for a speaker and Freightliner, International, and Volvo heavy vehicle manufactures supported 3 separate evening socials. Work continues on establishing the publisher for the conference proceedings.

Team members presented several papers at the conference and a large poster describing the goals and objectives of the DOE Project highlighting recent activities and results was constructed and displayed in the conference reception hall.

1.2 Working Group Meeting

A Working Group Meeting with the DOE Team and DOE representatives was held at the Asilomar in Monterey, California on December 4, 2003. Team members listed above as well as representatives from Georgia Tech Research Institute (GTRI) presented 'highlights' of most recent work that were not presented in their conference presentations. A major focus of the meeting was the recent experimental wind tunnel results with comparisons to field testing of the GTRI blowing device. A presentation by GTRI was followed by an extensive discussion of conclusions and the direction of future efforts related to the blowing device. NASA Ames presented highlights from recent 12-ft pressure wind tunnel experiments. LLNL presented their recent work on the design of innovative drag devices and planned wind tunnel experiments and computations. NASA and LLNL requested support for the proposed design experiments, NASA requested funds to complete the 12-ft pressure wind tunnel experiments, and LLNL requested funds to cover project management costs. DOE representatives Sid Diamond and Jules Routbort were in attendance and provided an update on the budget situation.

1.3 Conference Calls

The DOE Aero Team participated in a conference call on October 28th. The participants presented summaries of their planned activities, deliverables for FY03, and an update on their progress. The meeting emphasis was to discuss FY03 Statements of Work (SOW) and identify areas were modifications were needed to reflect issues raised at the September working group meeting. Some of these modifications included the addition of drag device 'discovery' experiments to be conducted by

NASA and LLNL, investigative studies of drag effects and drag reduction devices related to wheel wells and underbody flow, and investigative studies of drag effects for rail cars.

1.4 Statements of Work and Milestones for FY03

Modified statements of work with milestones for FY03 were constructed by each organization, reviewed as a group, discussed over a conference call on October 28th, and submitted to DOE.

1.5 Collaborations with Industry

Jim Ross of NASA Ames and Rose McCallen of LLNL are working with Matt Markstaller of Freightliner in constructing a proposal to DOE for an experimental and computational effort in anticipation of future DOE requests for proposals related to parasitic energy losses for heavy vehicles. A conference call with DOE representative Jules Routbort, Matt, Rose, and Jim was held on Nov 15^{th} to discuss proposal requirements and key issues.

1.6 Technical Accomplishments

Each organization has provided a one-page summary of their recent activities for the first quarter of FY03. Overall, progress has been good and we are well on our way to a successful year in achieving our goals and deliverables. In summary, the near-term deliverables are to provide industry with

Guidance on the use of computational tools

Insight into the flow phenomena for the design of low-drag heavy vehicles and

Design concepts developed from this insight.

The guidance on computational modeling will be accomplished through the analysis of existing data with comparison to our Reynolds averaged Navier-Stokes (RANS) and large-eddy simulations (LES) and a hybrid method called detached-eddy simulation (DES). An understanding of gap-flow, base drag, frontal flow, and the effect of drag reducing devices will be gained from experimental analysis as well as the validated computations.

2.0 Future Plans

Second entry experimental tests in the 12-ft pressure wind tunnel at NASA Ames are planed for February 2003.

DOE has requested that we continue communications and interactions with tractor manufacturers to provide encouragement for the newly formed Heavy Vehicle Aerodynamic Drag Industry Consortium. One suggestion was that we assist the consortium in defining and proposing a project where industry will jointly investigate the advantages of one or two aero devices and encourage fleet owners to utilize the device.

The Team will continue to have conference call meetings to share ideas, provide peer review, and keep each other up-to-date on our progress.

The next quarter will include a significant effort to publish the proceedings from the UEF conference. The Team members that presented at the conference are expected to submit their papers by the February 28^{th} deadline. Team members will also be asked by the chairs to assist in reviewing papers.

Lawrence Livermore National Laboratory

Activities for this quarter include both computational and experimental work. The focus of the computational effort has been the simulation of the gap flow and the trailer wake flow structures with the modified GTS geometry used in USC experiments and the original GTS geometry used in NASA experiments. The experimental data of USC and NASA are used to validate the calculations. The goal of the computational effort is to provide guidance on drag reduction strategies that could be implemented using add-on devices. The focus of the experimental effort is to provide insight into various drag reduction concepts. The small-scale 3'x4' wind tunnel at NASA Ames will provide an inexpensive and flexible way to fully investigate the selected drag reduction devices. The goal for the experimental investigation is to identify one or two add-on devices that clearly standout from other known and effective drag reduction devices. The selected add-on devices will then be presented to OEM's for further full-scale testing.

Flow Simulations

Simulations of the GTS in NASA's 7'x10' wind tunnel and the modified GTS in USC's tunnel are in progress. Steady and unsteady RANS (URANS) flow simulations are being performed with OVERFLOW. OVERFLOW is the NASA code that utilizes an overset grid technology which allows for the addition of geometrical components and complexities with ease.

The gap flow simulation was originally conducted with LLNL's ALE3D finite element method (FEM) code using a truncated trailer to reduce the number of elements in the computation. Since then, grids have been generated for the complete modified GTS in the USC tunnel that include the tractor and the trailer and a URANS simulation is currently in progress. Preliminary results are shown in Figure 1. Our goal is to understand the flow structure in the gap between the tractor and the trailer. With that knowledge, new add-on devices can be designed and tested to investigate their potential in reducing the aerodynamic drag due to the tractor-trailer gap.

LES of the trailer wake flow using LLNL's ALE3D FEM code with a truncated trailer geometry was presented at the UEF conference in December. Results indicate that the corners of the GTS geometry produce counter-rotating flow structures that are fairly robust and persist downstream of the massively separated wake (Figure 2).

To finally answer the question of how well RANS/URANS simulations can predict the bluff body flow field, two simulations have been setup: 1) GTS at NASA 7'x10' wind tunnel, 0° yaw, Re=2.0×10^6 based on trailer width, $M_\infty = 0.28$, k-ω turbulence model; 2) the same simulation as 1 but at 10° yaw. Both simulations will be generated using only the two-equation k-ω turbulence model. This decision was based on earlier work done at Sandia in 2001 where the one-equation Spallart-Allmaras (SA) turbulence model was used to simulate the flow field about the GTS model in the NASA tunnel. This work clearly indicated that the SA model did a reasonable job in predicting the flow field around the body but it failed to predict the flow structure in the wake of the trailer. The result of this investigation will be published in an SAE paper.

Generation of an overset grid for the GCM (AKA SLRT) geometry is in progress.

Discovery Experiment

'Discovery' experiments in the small-scale NASA Ames 3-ft x 4-ft wind tunnel are scheduled to begin in March of 2003. As was mentioned earlier, the purpose of these experiments is to provide an inexpensive and flexible means of testing and exploring various drag reduction concepts for heavy vehicles. Currently, a wind tunnel model (1/16 scaled) which is similar to the modified GTS is being designed and constructed. The add-on devices for drag reduction are also being designed.

Publication

The trailer wake LES flow simulation results presented at the UEF Conference in December will be published in the conference proceedings.

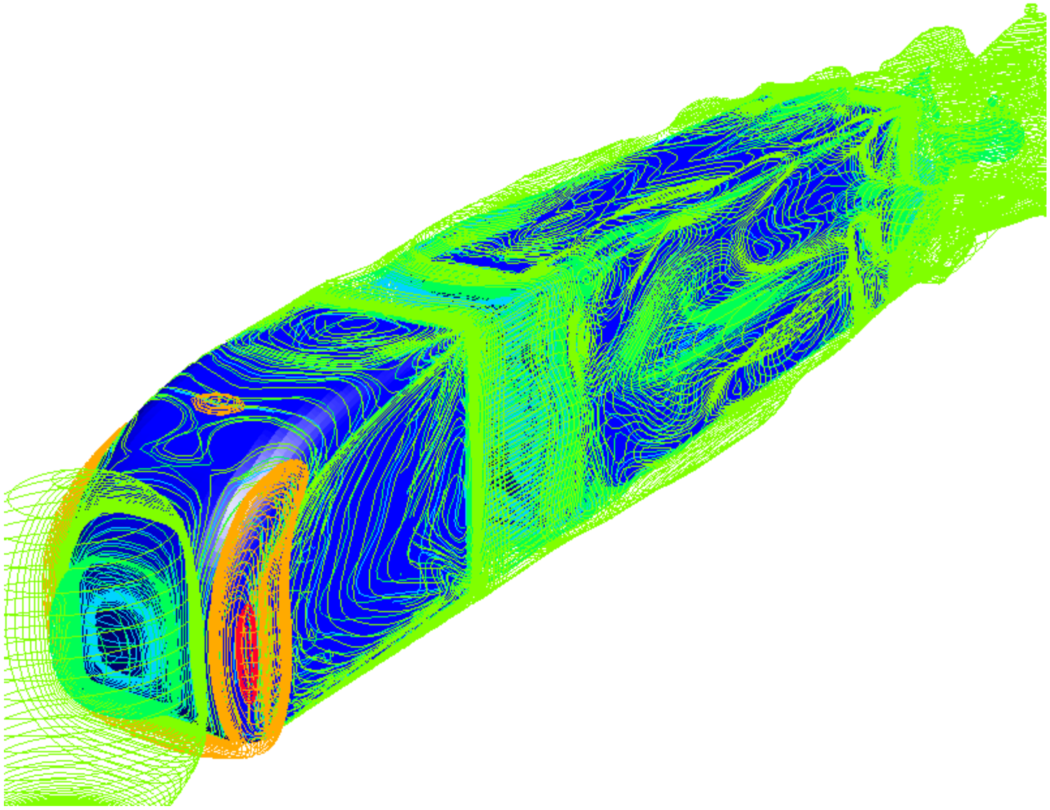

Figure 1. Preliminary results URANS simulation with the modified GTS geometry.

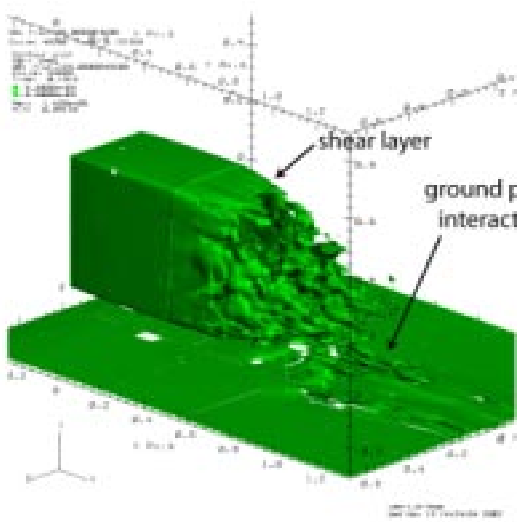

Figure 2. Isosurfaces of vorticty magnitude in the wake of the truncated GTS.

Sandia National Laboratories

SNL is responsible for evaluating the use of Reynolds Averaged Navier-Stokes (RANS) to predict the aerodynamic drag on a simplified model of a tractor-trailer vehicle. Over the past few years, Sandia's Navier-Stokes code, SACCARA, has been used to obtain RANS solutions using several different turbulence models. The results of these solutions indicated that the existing meshes did not have small enough spacing normal to the surface of the truck (i.e., y+ in normalized turbulence coordinates). In FY02, one of Sandia's goals was to generate new 3D meshes and to complete the evaluation of the RANS method. A 2D mesh generation study was done to help define required mesh spacing for the 3D meshes.

The finest 3D mesh was completed, and every other grid point was removed to obtain a coarser mesh which is referred to as the medium mesh. The medium mesh contained about 2.5 million cells and was decomposed, using Sandia's DECOMP code, into 125 zones. The solution was set up to run on 118 processors on the ASCI Red teraflop computer. Some zones were combined on a single processor in order to balance the loading of the processors. Solutions using the Menter hybrid k-omega/k-epsilon and the Wilcox (1998) k-omega turbulence models are fully converged and completed, with preliminary results shown at the United Engineering Foundation conference on the Aerodynamics of Heavy Vehicles.

A comparison of streamlines in a vertical cut through the wake region is shown below in Figs. 1a and 1b, where *x* is in the streamwise direction, and *y* is in the vertical direction. The base of the trailer is outlined in blue at the left-most side of the figures, and the window for the experimental ensemble-averaged PIV measurements is shown in red. The experiment (Fig. 1a) shows a large, counter-clockwise rotating vortex located at *x/W* = 8, *y/W* = 0.4. This vortex also appears in the computed results using the Wilcox k-omega model, although at a slightly lower vertical location. The presence of a clockwise rotating vortex is also shown in the computed results, however the experimental PIV window is not large enough to fully capture this feature. The three dimensional nature of the steady-state ensemble-averaged vortex core is depicted in Fig. 2. While these results with the medium mesh (2.5 million cells) are promising, the fine grid results are needed to give confidence that these results are fully converged in the wake region.

The fine mesh (20 million cells) has been decomposed and is currently running on approximately 950 processors on the ASCI Red machine. Results for both turbulence models are expected by the UEF conference paper deadline in March of 2003.

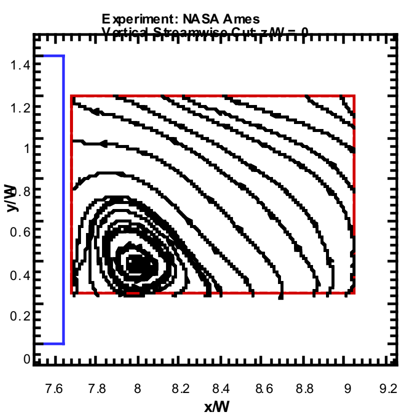

Fig. 1a: Experimental Streamlines

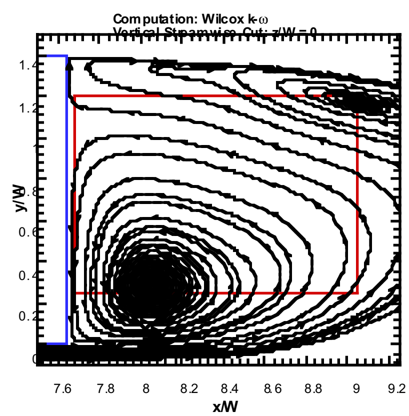

Fig. 1b: Computational Streamlines

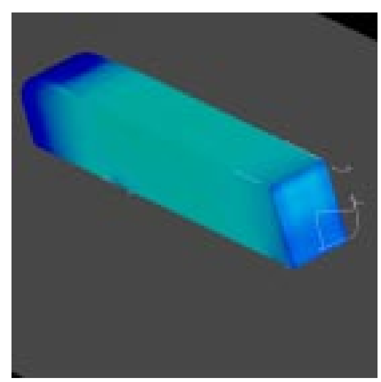

Fig. 2. Computed Vortex Cores

California Institute of Technology

Caltech's activities for the fourth quarter included participation in two conferences, one new publication, and continued research on the subjects of boundary treatment and time integration.

Work performed to date on multi-scale time integration was presented in a talk at the November meeting of the APS-DFD.

We also participated in December's United Engineering Foundation conference through collaboration with Goéric Daeninck of Grégoire Winckelmans' group at the Université Catholique de Louvain. Daeninck and Chatelain applied the group's vortex particle code to the GTS geometry. Our group's Closest Point Transform code (Figs. 1 and 2) now supports implicit transforms on irregularly-spaced particles in linear time, making it suitable for inclusion in the code.

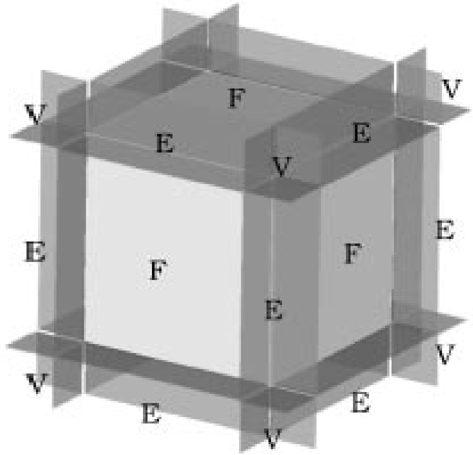

Figure 1: Characteristic regions of $|\nabla u| = 1$ outside a cube

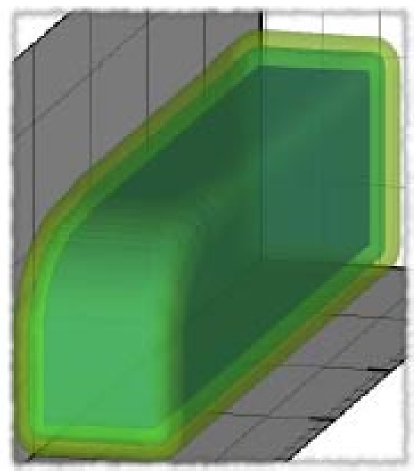

Figure 2: Isosurfaces of distance around the GTS geometry

A new paper on the spectral signatures of reconnecting vortex rings has been accepted for publication by Physical Review Letters. The topic of vortex ring reconnection has significance for turbulence modeling in vortex methods (Fig. 3).

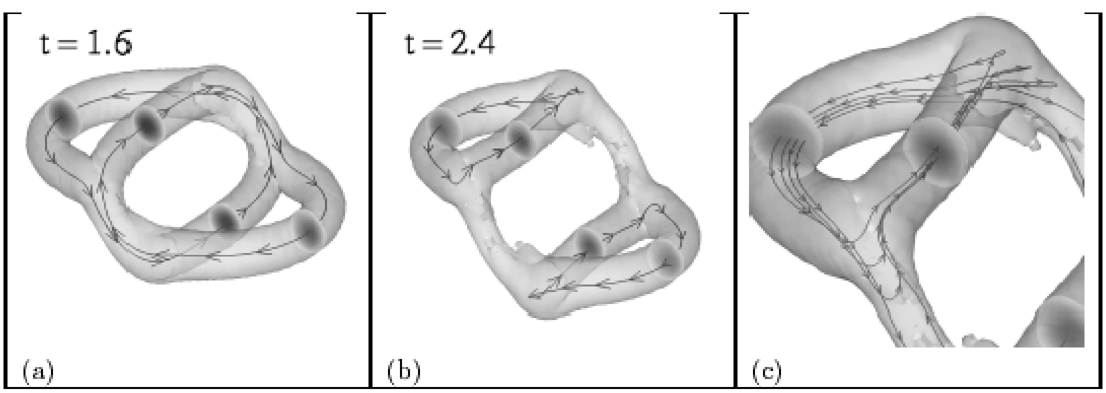

Figure 3: Vortex rings in an offset collision

Work also continues on a more general formulation of the boundary conditions. This will allow treatment of rotating and deforming objects by modeling fine scales in the near-wall region, and will help to reduce error along stream-aligned boundary corners.

NASA Ames Research Center

Experiments in 12-ft Pressure Wind Tunnel

The Generic Conventional Model (GCM) was tested in the NASA Ames 12-ft pressure wind tunnel during the month of November. The GCM is a one-eighth-scale model with high fidelity features in both the tractor and the trailer (Figure 1). This model was tested at pressures from 0.5 atmosphere to 6 atmospheres that provided Reynolds numbers ranging from 500,000 to over 6 million which corresponds to full-scale highway speeds. The particle image velocimetry (PIV) system did not function correctly in the pressure environment so those measurements were deferred for future tests. Several configurations demonstrated results different from the results gathered for the same model in the 7-ft x 10-ft wind tunnel, indicating some Reynolds number effects. A second entry is being prepared for February. PIV will be the primary goal for this second entry with aero testing of a few additional configurations.

Publication of 7-ft x 10-ft Wind Tunnel Results

In FY02, experiments of the GCM geometry in the NASA 7-ft x 10-ft wind tunnel were completed. Results from these experiments were presented in two papers at the UEF Conference held in Monterey, California in December. The results will be published in the conference proceedings.

Discovery Experiments

A collaborative effort with LLNL to experimentally investigate various drag-reduction concepts is one of the planned activities for FY03. These relatively inexpensive experiments will be conducted in the small-scale NASA Ames 3-ft x 4-ft wind tunnel that will offer ease and flexibility of geometry modifications. The vehicle model design is nearly complete and fabrication of the simplified GTS-like geometry should be relatively quick. Testing is targeted for March 2003.

Figure 1. GCM model in 12-ft pressure wind tunnel.

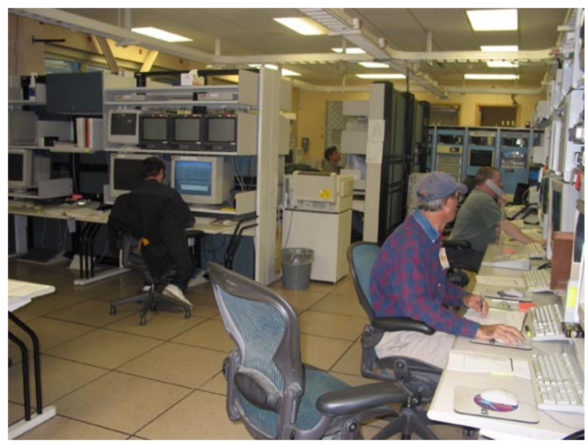

Figure 2. Control room of 12-ft pressure wind tunnel.

University of Southern California

Ground Vehicle Drag Reduction – Active Control to Reduce Base Drag of a Truck

This report describes the progress we have made to date on reducing the base drag of a truck with an active control approach (Figure 1). Included in this report is a description of work we have completed, work we are currently engaged in, and work we plan to complete in the near future.

Through our previous research, we have experimentally determined that the drag coefficient of our model decreases by approximately 20% with this trailer add-on device at the optimal flap angles. Furthermore, additional drag reduction was accomplished by introducing forcing at the base. This additional drag reduction was due to a net thrust generated by the oscillatory jet.

Presently, we are focusing on three aspects of the work. The first area is documentation of our existing research. We are in the process of documenting the UEF conference paper, which should be completed by the end of February, 2003.

The other two areas involve additional experiments. We are focusing our efforts on the various duty cycles of the forcing function. Hot film measurements at 1.5 mm downstream of the slot were used to understand the jet response to the duty cycle. These measurements will enhance the knowledge of producing zero net momentum flux flow by using the speaker as the forcing generator. The work in this area should also be completed in February, 2003.

Finally, due to the inaccuracy of the mechanism movement, we are currently developing a new design of the truck base. The current design has flap angle limitations, whereas the new design will provide a much wider range of flap angles, as well as four-side forcing. The new design also provides the option of relocating the slots upstream to the side wall, thus creating cross-flow fluctuation. It is our intention to have this new model completed by early March, 2003. Drag, hot film, and base pressure measurements will then be performed on this new design.

Through this research we hope to continue to address the issue of reducing base drag on a truck with an active control approach. We will continue to enhance our project with new design criteria as new challenges arise.

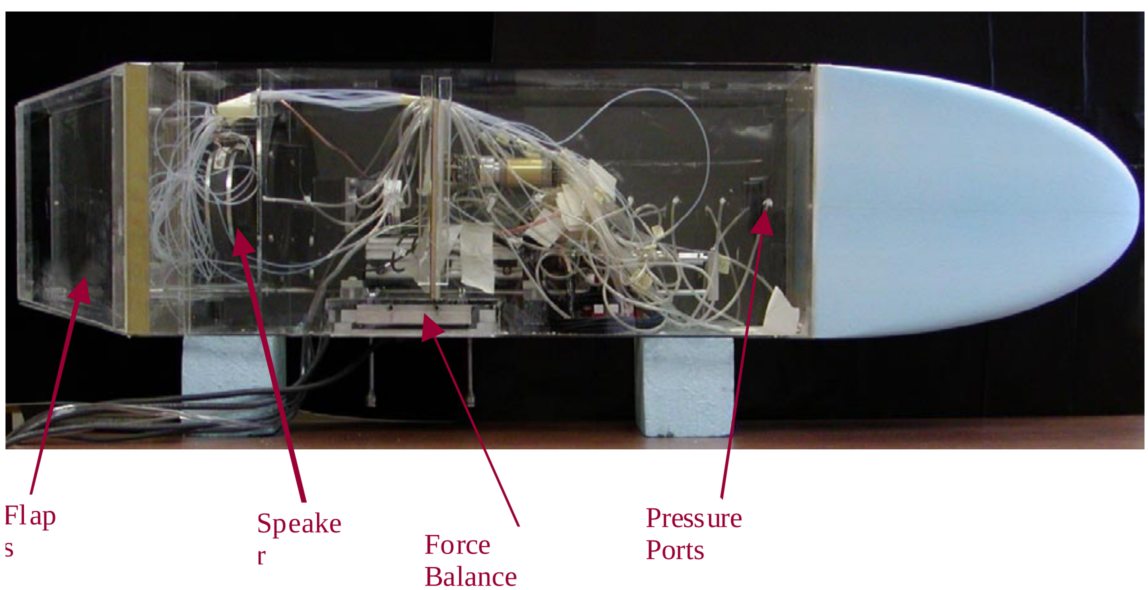

Figure 1. Active control device on model in USC wind tunnel.

Argonne National Laboratory

The proposed evaluation of commercial software capabilities for simulation of the aerodynamic drag of heavy vehicles was initiated in October 2002 following the signing of the Cooperative Research and Development Agreement with PACCAR Technical Center in late September 2002. In November 2002, David Pointer of Argonne and Paul Hancock of PACCAR met with Fred Ross of Adapco for a three day overview of the capabilities available in the latest version of the external aerodynamics tools wizard in Star-CD. Using these new capabilities, a Star-CD model of the standard truck variation of the GCM geometry was developed from the IGES data supplied by NASA Ames.

The Star-CD model of the GCM Standard Truck geometry uses approximately 4.5 million hexahedral and trimmed hexahedral cells in a partially unstructured mesh to represent a symmetric half of the truck model and the wind tunnel in the zero yaw angle case. The exact cross section of the 7-ft x 10-ft wind tunnel is utilized, but the velocity profile growth is resolved only for the floor of the tunnel. The inlet is located one model length upstream of the leading edge of the truck model and is specified by a uniform velocity condition. The outlet is located two model lengths downstream of the truck model and is specified by a uniform pressure condition. All cases in the preliminary study consider a Reynolds number of 1.1 million based upon the square root of the frontal area.

In these preliminary evaluations, the flow field surrounding the model is simulated using three different two-equation turbulence models. The first model considered is the standard k-epsilon model using a standard logarithmic wall function. The second model uses an alternate wall function formulation that emulates the SST model. The final model considered is the renormalization group or RNG model which reformulates both the governing equations and the wall function. Simulations using the SST model should provide some insight into the sensitivity of the solution to small changes in the wall function, and simulations using the RNG model should illustrate the effects of increased sensitivity to flow separation. Experimental measurements indicate a drag coefficient for the standard geometry of 0.4076 using a frontal area of .1544 m^2. Predicted drag coefficients from Star-CD simulations using the same frontal area are shown in Table 1. The velocity field at the centerline using the standard k-epsilon model is shown in Figure 1.

Upcoming efforts will focus on evaluation of the grid dependence of the solutions obtained and beginning the assessment of yaw angle effects for the GCM standard truck geometry. Additionally, the PACCAR-ANL team will begin to plan the instrumented experiments that will be used for evaluation of commercial code capabilities for real truck geometries.

Table 1. Comparison of Drag Coefficients from Star-CD Simulations and Experimental Measurements.

	Predicted/Measured Drag Coefficient	Percent Error
Experiment	.4076	–
Standard k-epsilon Model	.4095	0.46
RNG Model	.4003	1.81
SST Model	.4094	0.44

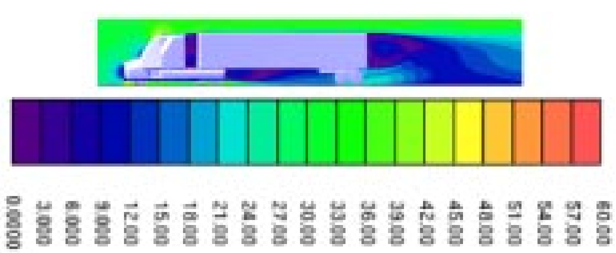

Figure 1. Velocity Profile at Model Centerline from Star-CD Simulation Using the Standard k-epsilon Model.